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Low-Energy Weak Interaction Physics in the LHC Era

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Precision measurements of observables in nuclear beta decay continue to provide important information on the structure and symmetries of the weak interaction. In this review the main focus is on the status and prospects of such measurements at radioactive ion beam facilities, often using atom or ion traps, in the era of the Large Hadron Collider.
With the precision of these measurements reaching the per mil level small Standard Model effects now have to be included as well. The understanding of some of these requires additional measurements be performed in order to maintain optimal sensitivity to weak interaction properties.

KEYWORDS: weak interaction, beta decay, physics beyond Standard Model, symmetries

1. Introduction

Over the years low-energy experiments with atomic and nuclear systems have provided significant contributions to the Standard Model (SM) of fundamental particles and interactions. This is still the case today [1, 2] by virtue of new techniques, such as ion and atom traps, and the ever increasing sensitivity of the methods applied. Properties of the SM are thus tested with high precision, or new types of weak interaction are searched for by looking for small deviations from the SM-predicted values of experimental observables. Even with the Large Hadron Collider running at good pace and searching for the direct production of new bosons related to as yet unobserved weak interaction types, measurements at low energies remain competitive provided observables are well selected and the sensitivity, and thus the experimental precision, continue to be improved.

Here, a brief but non-exhaustive overview will be given of recent and ongoing achievements related to i) atomic parity violation tests and electric dipole moment searches, ii) the determination of the V_{ud} quark-mixing matrix element and iii) searches for exotic (scalar and tensor) weak currents with radioactive isotopes. New vistas and prospects for this field in the era of the LHC will be discussed as well.

2. Atomic Parity Violation Tests and Electric Dipole Moment Searches

2.1 Atomic Parity Violation Tests

Atomic parity violation (APV) tests are probing the value of the weak mixing angle (Weinberg angle), $sin^2\,\theta_W$, which relates the masses of the $W^{\pm}$- and Z^0-bosons, in the eV-range. As to radioactive probes, experiments with francium isotopes are currently being prepared at LNL (TRAPPRAD experiment) [3], TRIUMF (Canada) [4] and CYRIC (Japan) [5], while tests of APV with a single radium ion are ongoing at the University of Groningen [6]. New and precise measurements with high-Z francium and radium isotopes, although these are radioactive and so less copiously available, are important since the parity non-conserving effect increases faster than Z^3 and because the near degeneracy of atomic levels with opposite parity is leading to enhancement factors that are up to several orders of magnitude higher (e.g. [7]) compared to the already very well studied ^{133}Cs system [8]. Further, experiments with a single (stable) barium ion are in preparation at Seattle [9], while other APV measurements with stable atoms and molecules are discussed in e.g. [4].

2.2 Electric Dipole Moment Searches

A permanent electric dipole moment (EDM) for a particle violates both parity and time reversal and therefore, accepting the CPT theorem, also the CP symmetry. CP violation, together with the violation of charge conjugation and baryon number and a departure from the thermal equilibrium in the early Universe, was put forward by Sacharov [10] as a necessary condition for the observed large difference between the amount of matter and anti-matter in the universe (the so-called baryon asymmetry). The CP violation that is included in the SM via the phase in the Cabibbo-Kobayashi-Maskawa quark-mixing matrix [11] is too small to explain this baryon asymmetry. EDM experiments search for stronger sources of CP violation. Such experiments are further complementary to the search for supersymmetric extensions of the SM since most SUSY models predict non-zero EDMs.

EDMs are being searched for in different systems, ranging from fundamental particles (e.g. electron and muon), over the neutron, atoms and nuclei and even molecules. Measurements in different systems provide complementary information as to the origin of the EDM (and CP violation) if a non-zero value would be found in one or more systems. EDM experiments with radioactive probe nuclei are being prepared with ^{223}Rn at TRIUMF [12], with francium at Tokohu Univ., Japan [5], and with ^{225}Ra at the University of Groningen [13] and at Argonne Natl. Laboratory [14]. An overview of experiments with stable probes can be found in e.g. [15].

3. The V_{ud} CKM quark-mixing matrix element and unitarity

Over the years an impressive set of measurements of Q_{EC} values, half-lives and branching ratios leading to corrected $\mathcal{F}t$ values for a set of 20 superallowed $0^+ \to 0^+$ pure Fermi β transitions has been collected [16]. These constitute a very strong test (1.2×10^{-4} level) of the Conserved Vector Current hypothesis [17] and have provided a very precise value for the V_{ud} quark-mixing matrix element. At the same time new and more precise experimental data for kaon decays as well as more precise lattice QCD calculations of form factors relevant for deducing the $|V_{us}|$ matrix element from experimental data, have become available as well (e.g. [16, 18, 19]). This has allowed to test the unitarity of the CKM matrix at the 5.5×10^{-4} level, i.e. $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.99978(55)$ [16].

Future significant progress in the precision of $|V_{ud}|$ requires (e.g. [20]) i) new and more precise data for several of the three input quantities for the pure Fermi transitions, but also ii) extending the actual data set to new and possibly also heavier isotopes, i.e. above ^{74}Rb [21], iii) improving the precision to which the nucleus-dependent isospin correction δ_C is understood [16,22] and, finally, iv) a further increase in precision for the nucleus-independent radiative correction Δ_R [23]. Efforts are continuously ongoing at several laboratories, e.g. ISOLDE-CERN, JYFL-Jyväskylä, and TRIUMF, to further improve and extend the experimental input data and the knowledge of the δ_C correction.

Recently it was pointed out [24] that the isospin T = 1/2 mirror β transitions provide an independent check of the CVC hypothesis and can also contribute to the determination of the V_{ud} matrix element. They could, in addition, also help consolidating and refining the calculations of the isospin-symmetry-breaking correction δ_C. As these are mixed Fermi/Gamow-Teller (F/GT) transitions the ft value now also has to be corrected for the F/GT mixing ratio, ρ, to yield:

$$\mathcal{F}t_0 = ft(1+\delta_R')(1+\delta_{\rm NS}-\delta_C)\left[1+(f_A/f_V)\rho^2\right] = \frac{K}{G_F^2 V_{ud}^2(1+\Delta_R^V)} \ , \tag{1}$$

with $\delta_{\rm R}'$ and $\delta_{\rm NS}$ a nucleus-dependent, respectively nuclear structure-dependent radiative correction, f_A/f_V the ratio of the axial-vector and vector form factors, G_F the Fermi coupling constant, and K

a combination of fundamental constants [**?**]. Using results from published experiments, that were originally not performed for this purpose, a value of $|V_{ud}| = 0.9719(17)$ was already obtained [24]. Future prospects will be discussed in Sect. 6.

It is to be noted that $|V_{ud}|$ can also be obtained from neutron decay. This has the advantage that it is independent of nuclear structure corrections. However, before a reliable and precise value for $|V_{ud}|$ can be obtained reliable values for the neutron lifetime [25, 26] and the neutron β-asymmetry parameter [27] should be available. New results [28–31] seem to indicate that the relevant systematics will most probably rather soon be sufficiently well under control.

Finally, as to the value for $|V_{us}|$, a very recent new lattice QCD calculation of the semileptonic form factor $f_+(0)$ in kaon decay has created a 2σ tension with the SM [32]. This issue clearly has to be solved as soon as possible.

4. Exotic weak currents

Information on exotic, scalar (S) and tensor (T) weak currents has recently primarily been obtained from β-ν correlation and β-asymmetry parameter measurements as well as from the average $\mathcal{F}t$ value of the superallowed Fermi transitions. The latter two depend, via the so-called Fierz interference term [33], linearly on the coupling constants, yielding narrow bands that extend to infinity for the allowed regions in the C_i versus C_i' (with i = S, T) parameter plane (the relative magnitude of the primed and unprimed coupling constants determines the properties of the interaction under the parity operation). The β-ν correlation, a, on the other hand, depends both linearly (i.e. via the Fierz term in the actual quantity that is determined experimentally, viz. $\tilde{a} = a/[1 + (\gamma m_e/\langle E_\beta\rangle)\ b_{Fierz}]$, with $\gamma = \sqrt{1-(\alpha Z)^2}$), as well as quadratically on the coupling constants, resulting in donut-shaped allowed regions. The different observables thus produce complementary constraints on S and T couplings.

4.1 Scalar weak currents

Strong limits on scalar weak coupling constants have been obtained by combining the narrow band of allowed values obtained from the average $\mathcal{F}t$ value of the superallowed Fermi transitions [?] with the donut-shaped allowed region from β-ν correlation measurements. Most recent experiments of the latter type use atom or ion traps [2, 34]. The most precise result till now was obtained with ^{38m}K using the TRINAT Magneto Optical Trap (MOT)-based setup at TRIUMF, Vancouver, i.e. $\widetilde{a} = 0.9981(30)(34)$ [35]. It is fair to mention here also the result obtained in the mid-1990's by Adelberger et al. [36] with ^{32}Ar at ISOLDE-CERN, i.e. $\widetilde{a} = 0.9989(52)(39)$. They measured the Doppler broadening of the β-delayed proton peak following the superallowed decay of ^{32}Ar. At Texas A&M University a Penning trap-based apparatus is now being set up to perform this type of measurements also for other light-mass isotopes [37, 38].

Another MOT-based experiment, which was performed at Berkeley National Laboratory, provided an about 1% relative precision for the β-ν correlation, a, in the decay of the mixed F/GT (but mostly Fermi type) β decay of ^{21}Na [39]. From an earlier experiment with the same isotope and setup [40] it had become clear that a too large source strength in a MOT can lead to the formation of molecules causing a systematic shift in the value of the correlation coefficient.

Finally, β-ν correlation measurements in the F/GT mixed mirror β decays of ^{35}Ar and ^{19}Ne recently performed with the LPCTrap setup at GANIL [41–43] (see also Sec. 6.3), and for ^{35}Ar with the Penning trap-based WITCH experiment [44–46], are also sensitive to scalar weak currents.

4.2 Tensor currents

The strongest limits on tensor type weak currents from a single experiment are from the β-ν correlation measurement performed with ^{6}He by Johnson et al. [47]. New measurements of this correlation with the same isotope with the LPCTrap device at GANIL have already lead to an about 3% relative precision, i.e. $\widetilde{a} = -0.33335(73)(75)$ [48], while analysis of a larger data set, corresponding to an about 0.5% (statistical) relative precision, is ongoing [43]. Further, two other experiments to determine the β-ν correlation in the decay of ^{6}He are ongoing at the Univ. of Seattle (Washington, U.S.A.) [49, 50] and at the Weizmann Institute (Rehovot, Israel) [52].

At Argonne National Laboratory the $\beta - \nu$ correlation in the predominantly GT β-decay of the ^{8}Li ground state to the first excited state in ^{8}Be that immediately breaks up into two α particles was determined by inferring the momentum of the neutrino from the kinematic shifts of these breakup α particles [51]. The result of a first measurement with this setup yielded $|C_T/C_A|^2 = 0.004 \pm 0.009_{stat} \pm 0.010_{syst}$ [51] and is equivalent to $a_{\beta\nu} = 0.3307(60)_{stat}(67)_{syst}$, i.e. an about 3% precision for $a_{\beta\nu}$, in agreement with the Standard Model value of -1/3 and with the results from Refs. [47] and [48]. The authors anticipate an improvement by up to an order of magnitude with an upgraded detector system and much better statistics, which would also allow studying the small recoil-order terms as well as possible effects of second-class currents [51].

In the past decade the Leuven group has performed measurements of the β-asymmetry parameter for three pure GT β decays, yielding information on tensor weak currents via the Fierz interference term which is complementary to the limits obtained from β-ν correlation measurements. The β-asymmetry measurements with ^{60}Co [53], ^{67}Cu [54], and ^{114}In [55] constitute the most precise measurements of this parameter for nuclear β decays. The low-temperature nuclear orientation technique was used (e.g. [56]). Effects from scattering and from the external magnetic field on the trajectory of the β particles was taken into account via a Geant4-based simulation code that had been developed especially for this purpose [57, 58]. Simulated data (assuming the SM value for the β-asymmetry parameter, A) were analyzed in exactly the same way as the real data. The constancy (within error bars) of the ratio A_{exp}/A_{sim} when the β spectrum was divided into energy bins showed the good quality of the simulation code as most effects it has to take into account are energy dependent.

5. Charge state distributions

In several of the experiments mentioned above the charge state distributions of the daughter isotope after β decay in a MOT or Paul trap have been deduced as well [59–62]. Comparing these results with theoretical calculations can provide interesting information on the atomic aspects of the decay process. For ^{6}He perfect agreement with theoretical calculations was found [61], while for ^{35}Ar calculations clearly showed the importance of Auger processes in heavier atoms [62].

6. New Vistas and Prospects in the Era of the LHC

Recently, a unified Effective Field Theory framework based on a quark-lepton level effective Lagrangian (e.g. [63]) was put forward. Assuming the new physics to emerge only at an energy scale well above the production threshold of the LHC (such that LHC experiments are in fact also 'low-energy' experiments), results from β-decay and searches at the LHC can be compared in a rather model-independent way. It was shown that low- and high-energy searches for new CP-conserving scalar and tensor interactions involving left-handed neutrinos are competitive and remain so even after the energy and intensity upgrades of the LHC if precisions of the order of 10^{-3} are reached for the Fierz interference term [63,64] (see also [65]). Thus, if new bosons are found at the LHC, β-decay experiments can play an important role in determining their properties. In view of further significant progress with β-decay experiments it is therefore necessary to i) continue improving the sensitivity of correlation measurements so as to reach the 10^{-3} level and beyond (e.g. [66]), ii) further improve the precision on $|V_{ud}|$, and iii) extend the number of variables that can be addressed experimentally also to correlations with polarized nuclei, if possible in traps, and the β-spectrum shape.

6.1 Correlations with polarized nuclei

When nuclei are polarized β-decay correlations other than the β-ν correlation become accessible as well, such as e.g. the β-asymmetry parameter, A, and the neutrino-asymmetry parameter, B, or even the D-triple correlation [1, 33]. This would significantly extend the number of observables accessible with traps, allowing to also perform a new class of parity and time-reversal violation tests, taking advantage of the excellent sample conditions that are offered by traps.

First measurements with polarized samples in traps have been performed already. At TRIUMF the TRINAT team has measured the neutrino-asymmetry parameter, B, in the decay of ^{37}K [67], while the asymmetry of the daughter nuclei after β decay, i.e. the parameter $A + B$, has been investigated in the decay of ^{80}Rb [68]. In both cases the isotopes in the MOT trap were polarized by optical pumping. The degree of nuclear polarization was determined by photoionizing atoms from the excited states in the optical pumping process. At Los Alamos Natl. Laboratory a nuclear polarization as high as 99.2(2)% and determined with per mil precision has been achieved for Rb using this method [69].

Measurements with polarized isotopes in a MOT are also being prepared for ^{19}Ne in Israel (Jerusalem-Tel Aviv-Rehovot collaboration) [70] and with ^{35}Ar at the Univ. of Liége [71]. Other experiments, with isotopes polarized by collinear laser optical pumping, not involving traps, will be discussed in Sec. 6.3.

6.2 β-spectrum shape measurements

As the most recent high-precision β-spectrum shape measurements were performed already about 25 years ago, and in view of a number of recent technical developments in data acquisition and detection techniques, the β-spectrum shape is at present a potentially very interesting observable. For our purposes the shape of the β spectrum can be written as

$$d\Gamma \propto G_F F(Z,E)\left[1 + \frac{k_1}{E_\beta} b_{Fierz} + k_2 E_\beta b_{WM}\right] \tag{2}$$

with $F(Z,E)$ the Fermi function, E_β the energy of the β-particle, b_{Fierz} the Fierz interference term and b_{WM} the so-called weak magnetism form factor [72]. The latter term is present in the SM and is induced by the strong interaction because the decaying quark is not a free particle but is bound inside a nucleon. The effect of this on the value of correlation coefficients is typically of the order of a few per mil, but can amount to about 1% in retarded β transitions [53]. With the precision of correlation measurements now being at the sub-percent level, weak magnetism should thus be taken into account when extracting new information on exotic currents from e.g. the Fierz interference term. Whereas other effects of similar size, such as e.g. radiative corrections, are well understood and can be calculated to good precision, weak magnetism has until now only been studied for a number of low-mass (i.e. up to A = 30) isotopes [73] and additional information is more than welcome. As the weak magnetism term is proportional to E_β, transitions with high endpoint energy are preferred. Further, as the energy dependence of the β-spectrum shape for the Fierz and weak magnetism terms are complementary, both effects can be studied with only limited disturbance from each other.

Teams from the universities of Cracow and Leuven, together with colleagues from Kentucky and Prague, are setting up different types of spectrometers for precision β-spectrum shape measurements. In the first, called miniBETA, the source is placed between two identical multi-wire drift chambers (MWDC) [74] with two plastic scintillators providing the trigger for the readout. The concept for the MWDC's is based on the multi-wire proportional chambers that were used in previous experiments [75, 76]. Each MWDC (fiducial volume of 20 x 20 x 10 cm^3) consists of 5 planes with 8 cathode wires each. The energy of the β particles will be obtained from the curvature of their trajectories in a magnetic field. With this method, scattering effects are inherently small and are mainly due to the thin source foil, the about 300 mbar gas filling, and the thin wires.

A second type of β-spectrometer uses two semiconductor detectors placed opposite to each other in a strong magnetic field and with the source between the two detectors. The magnetic field is set such that the radius of curvature of the β-particle trajectories is smaller than the radius of the detectors. β particles scattering or bouncing back from one detector will end up on the other one. The full energy of the β-particles is then obtained by adding the energy signals from both detectors. The use of digital electronics allows for high quality data. Previously it has been shown that pure Si and Ge detectors can be operated at temperatures down to 10 K [77–79] and in magnetic fields up to 13 T [80,81], with good performance and with an energy resolution of about 5 keV.

Both types of setup have an almost 4π solid angle which is several orders of magnitude larger than for magnetic spectrometers. In addition, systematic errors are very different so that measurements with both spectrometers will cross check each other. Measurements with ^{45}Ca ($t_{1/2}$ = 163 d, β-endpoint energy E_0 = 256 keV) to determine the Fierz interference term are already ongoing, while measurements with ^{114}In ($t_{1/2}$ = 50 d, E_0 = 1.99 MeV) focusing mainly on the weak magnetism form factor are being planned. Other β decays of interest are e.g. those of ^{14}C ($\log ft$ = 9.0) and ^{32}P ($\log ft$ = 7.9), in which the GT matrix element is strongly suppressed due to the large ft values.

The miniBETA spectrometer provides also a unique opportunity to study the (back)scattering and transmission of β-particles on, respectively through different materials. Such data will allow improving the precision and reliability of the Geant code which plays an important role in the analysis of β correlation and spectrum shape measurements.

Finally, β spectrum shape measurements are also ongoing at e.g. MSU-NSCL (Michigan). A high purity beam of ^{6}He nuclei is implanted into a thick scintillator [82]. All electrons from ^{6}He decay are thus confined within the detector volume, thereby eliminating effects of scattering.

6.3 The V_{ud} matrix element from mirror β decays

As was mentioned already in Sect. 3, precise determinations of the $\mathcal{F}t$ values and F/GT mixing ratios for mirror β transitions could help to further improve the precision on $|V_{ud}|$. The corrected $\mathcal{F}t$ values for these transitions have recently been calculated already [83]. The mixing ratio, ρ, has to be extracted from a correlation measurement, e.g. the β-ν correlation or the β-asymmetry parameter. To this end β-ν correlation measurements have recently been performed at GANIL-Caen with the Paul trap-based LPCTrap setup with the isotopes ^{35}Ar and ^{19}Ne [42,43] and additional measurements with the mirror isotopes ^{21}Na, ^{23}Mg, ^{33}Cl and ^{37}K are being planned at GANIL following the SPIRAL1 accelerator complex upgrade [43]. Further, a measurement of the beta-asymmetry parameter with polarized ^{37}K is already ongoing at TRIUMF [38]. Estimates show [43] that these measurements with mirror transitions could provide together an absolute error on $|V_{ud}|$ of about 0.0004 to 0.0005, which is only a factor of two worse than the value of 0.00022 obtained from the entire set of 13 high-precision superallowed Fermi transitions [?].

Further, it was shown recently [84] that for mirror β transitions the highest sensitivity to $|V_{ud}|$ can be obtained if the F/GT-mixing ratio of ^{35}Ar is deduced from the β-asymmetry parameter. In this case a measurement with a relative precision of 0.5% yields an absolute uncertainty on $|V_{ud}|$ of 0.0007 with the current $\mathcal{F}t_0$ value [83], and 0.0004 if the $\mathcal{F}t_0$ value can be improved by a factor of about 5 [84]. Efforts with respect to the latter are ongoing at ISAC-TRIUMF [85] and at JYFL-Jyväskylä [86]. The β-asymmetry of ^{35}Ar would thus play a major role within the total mirror nuclei data set contributing to $|V_{ud}|$. Measurements of the β-asymmetry parameter for the mirror decay of ^{35}Ar are being prepared using two different methods for producing the polarized sample. The first (by a collaboration of the Universities of Liège and Leuven, Belgium) will use a MOT-trap-based setup [71] and observe the β-decays in the trapped atom cloud that will be polarized by optical pumping. The second (by a collaboration between the Universities of Leuven, Liège and Michigan, together with ISOLDE and other institutes) will polarize the ^{35}Ar beam by collinear laser optical pumping [87]. A complementary project is ongoing at the BECOLA facility at the NSCL [88,89] focusing primarily on ^{21}Na and ^{37}K.

7. Conclusion

An overview was given of the status, planned experiments as well as prospects and new vistas in the era of the LHC for low-energy weak interaction studies in nuclear β decay. It was shown that further improvements of the $\mathcal{F}t$ value for the pure Fermi β transitions and dedicated experiments to determine the $\mathcal{F}t_0$ value for mirror β transitions corrected for the F/GT mixing ratio, could significantly improve the precision of the V_{ud} quark-mixing matrix element. Further, searches for exotic scalar and tensor weak currents would highly benefit (and remain competitive to direct searches at the LHC) from β-decay correlation measurements and β-spectrum shape measurements with precisions at the per mil level. The latter would also provide important additional information on the weak magnetism correction induced by the strong interaction that has to be considered at this level of precision. Finally, further developments towards polarized samples in atom and ion traps would extend the number of observables accessible with traps, allowing to also perform a new class of parity and time-reversal violation tests.

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